ADVANCED MIRROR SYSTEM DEMONSTRATOR (AMSD)

PROGRESS UPDATE
AT
GOODRICH ELECTRO-OPTICAL SYSTEMS

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NASA Technology Days
Marshall Space Flight Center
May 22-23, 2002

Agenda

- Program Objectives and Requirements
- Goodrich Configuration Overview
- Progress Update and Status
  - Facesheet
  - Actuators and Controller
  - Reaction Structure
  - Assembly and Integration
- Test Plan and Program Schedule
- Summary and Conclusions

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AMSD Program Objectives

- **Diverse government applications require the benefits of:**
  - **High-payoff large, light-weight mirrors**
    - **that advance the state of the art, <u>and</u>**
    - **are rapidly producible, <u>and</u>**
    - **are affordable**

- **Specific objectives:**
  - **Sub-scale demo of the mirror system technology**
  - **Traceable growth path to deployable, segmented optical systems**
  - **Provide design features that enable/improve the manufacture, integration, test, and performance of a broad range of operational systems**

Summary of Requirements and Compliance (1 of 2)

REQUIREMENT	STATUS/COMMENT
Physical	
- < 15 kg m^{-2}	*~ 16.7 kg m^{-2} (actuators + CRS repair)*
- Hexagonal shape	*Comply (V-notch to eliminate fracture)*
- 1.2m to 1.5m point-to-point	*Comply (1.3 m point-to-point)*
Mechanical	
- Fundamental frequency traceable to full-size flight mirror system	*Comply*
Ambient Environment	
- 290K to 310K	*Comply*
- External mechanical disturbances	*Comply*
Cryogenic Environment	
- 30K to 55K	*Comply*
- No mechanical disturbances	*Comply*
Survival Environment	
- 223K to 353K	*223K to 324K (limited by adhesive)*
•25K to 353K (cryogenic)	*Comply*
- 10g quasi static	*Comply*
- 30g vibroacoustic	

Summary of Requirements and Compliance (2 of 2)

REQUIREMENT	STATUS/COMMENT
Total Surface Error	
- 50 nm (rms); 250 nm (P-V)	*Compliance expected*
- Goal 25 nm (rms); 100 nm (P-V)	*Achievable with additional CCP cycles*
Micro-roughness	
- 40 Å (rms)	*Compliance expected*
- Goal of 20Å (rms)	*Compliance expected (< 20Å typical for glass)*
- Spatial periods 1 mm to 1 µm	*Comply*
Prescription	
- Off-axis parabola	*Comply*
Vertex Radius of Curvature	
- 10.000m ± 1mm	*Comply*
Coating	
- No coating required	*Comply (no coating)*

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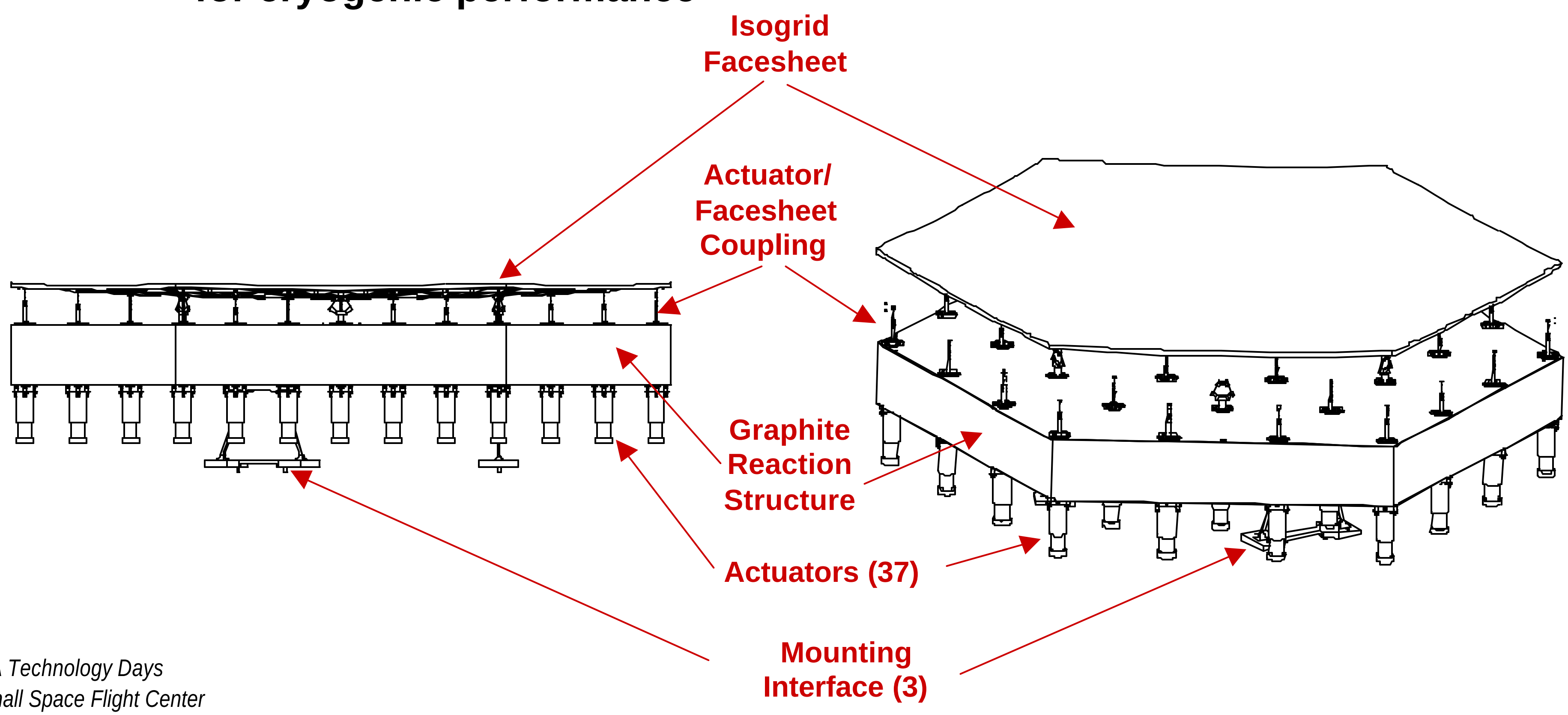
Design Concept

Architecture:

- Thin, light-weighted mirror facesheet
- Array of figure-control actuators
- Passive, stiff reaction structure
- Mirror facesheet CTE and DL/L matched to reaction structure for cryogenic performance



Design Approach

- **Figure-controlled (adaptive) mirror**
  - Reduces fabrication/test cost and schedule
  - Maximizes operational system applicability
- **Mirror facesheet CTE and $\Delta L/L$ matched to reaction structure**
  - Enables cryogenic performance
- **Multiple material options (mirror/reaction structure pairings) from a single architecture**
- **Design optimization to mission constraints**
  - Environment
  - Performance
  - Cost
  - Schedule
  - Actuator design is common
  - Mirror facesheet and reaction structure details are material dependent
  - Traceability assessments are material dependent
    - Influenced by specific application
    - Material dependent processes and facilities

Design Approach Benefits

- **Cost and schedule effective optical manufacturing**
  - **Non-recurring investment in tooling, followed by rapid fabrication of multiple matched facesheets**
  - **Work with large tools for majority of processing time**
  - **Actuators for low spatial frequency correction**
  - **Computer Controlled Polishing (CCP) for remainder**

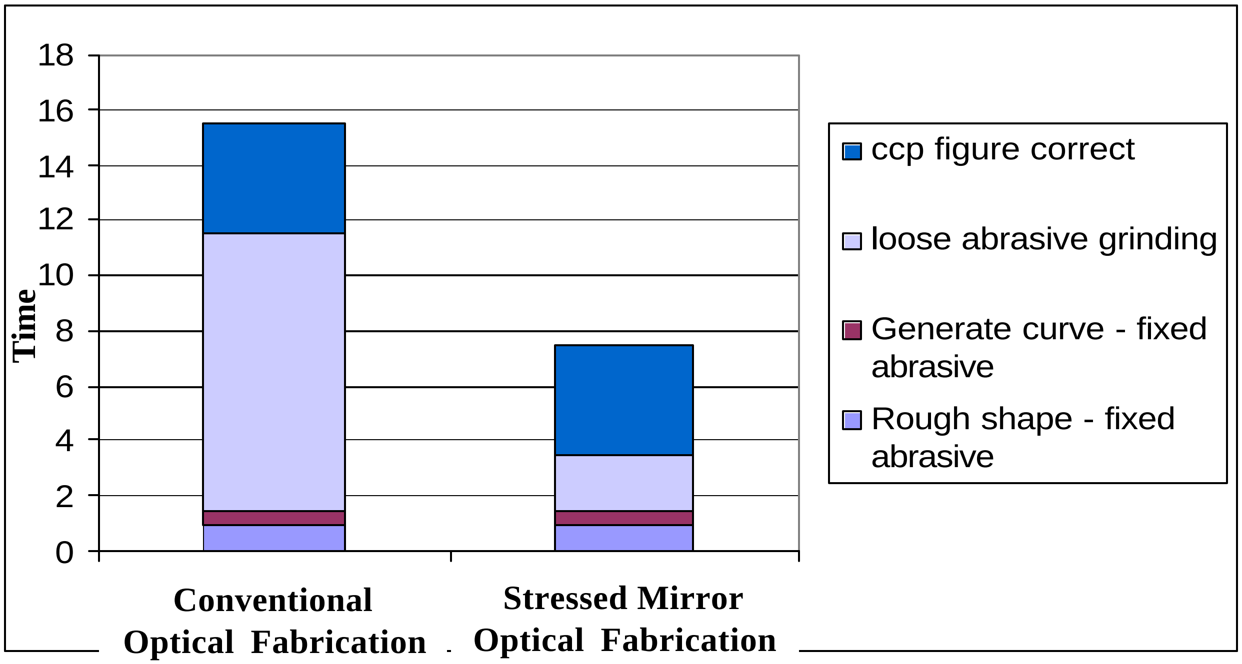
- **Cost and schedule effective system-level operations**
  - **Actuators provide radius and figure adjustment at test and operating temperatures**
  - **Flexible substrate allows increased shape correction**
  - **Reduced reliance on ground testing**

Approach for Optical Fabrication:
Stressed Mirror Polishing Overview

- **Basic fabrication process referred to as "Stressed Mirror Polishing" (SMP)**
  - **R2 (backside) of optic is fabricated to a sphere**
  - **Optic is held, by vacuum, against aspheric blocking body**
  - **Blocking body asphericity is negative of desired R1 asphericity**
  - **R1 is polished to a sphere**
  - **When vacuum is released, R1 will "spring" to desired asphere**
  - **Touch-up polishing after mounting to actuators**
- **SMP process has several advantages**
  - **Spherical fabrication process is fast, smooth, and simple**
  - **Minimal optic handling reduces risk - most of the time the optic is mounted to granite blocking body**
  - **For multiple optics of same form, investment in blocking body paid off early**

Fabrication of Fast Aspheres by SMP

- **Taking advantage of thin section, bend the mirror to look like a sphere; grind and polish a sphere**
- **Large tools can remove material damage layer much faster**
- **Return to small-tool processing of unstressed asphere for final figure correction**



Recurring and non-recurring efforts tailored based on quantity of units.

AMSD Approach Leverages Demonstrated Large Optical Systems Technology

- **HALO**
  - **3-meter diameter Primary Mirror Assembly**
  - **30 kg/m^2**
  - **tested at 100 Kelvin**
- **LAMP**
  - **4-meter diameter Primary Mirror Assembly**
  - **room temperature High Energy Laser System**
- **ALOT**
  - **4-meter diameter lightweight telescope for space operation**
  - **70 kg/m^2 PMA**
  - **room temperature imaging system**
- **LOS**
  - **two four-meter diameter segments of 11-meter, f/1.25 primary mirror**

Large, segmented mirrors and telescopes benefiting from shape-controlled technology are demonstrated.

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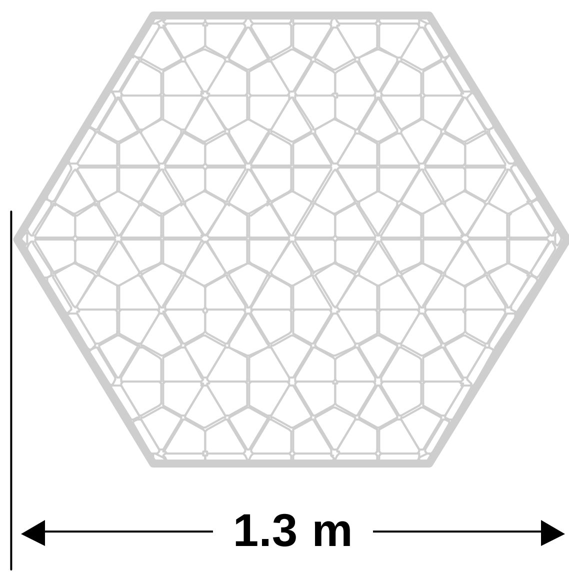
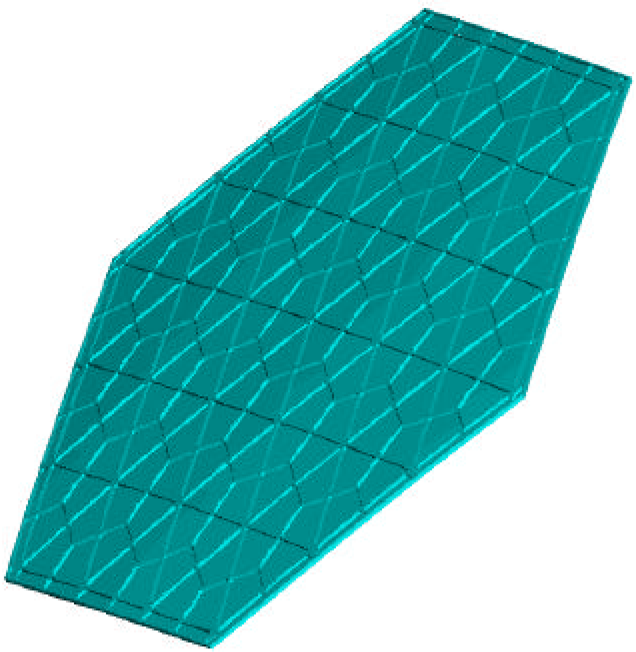
Light-Weighted Thin Facesheet:

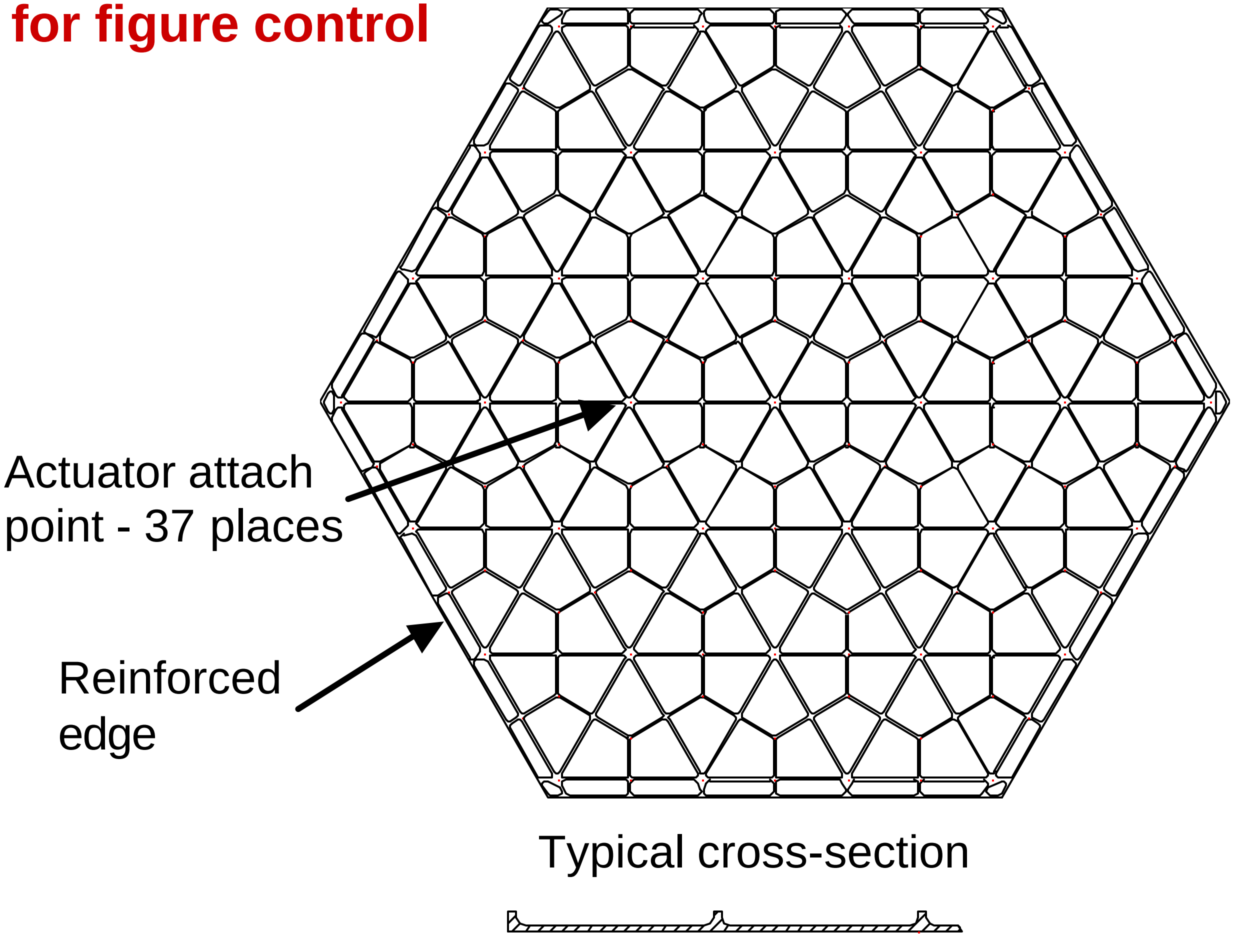
- **Facesheet design**
- **Optical fabrication (SMP)**
- **Light-weighting and edging**
- **Fracture and recovery**
- **Status**



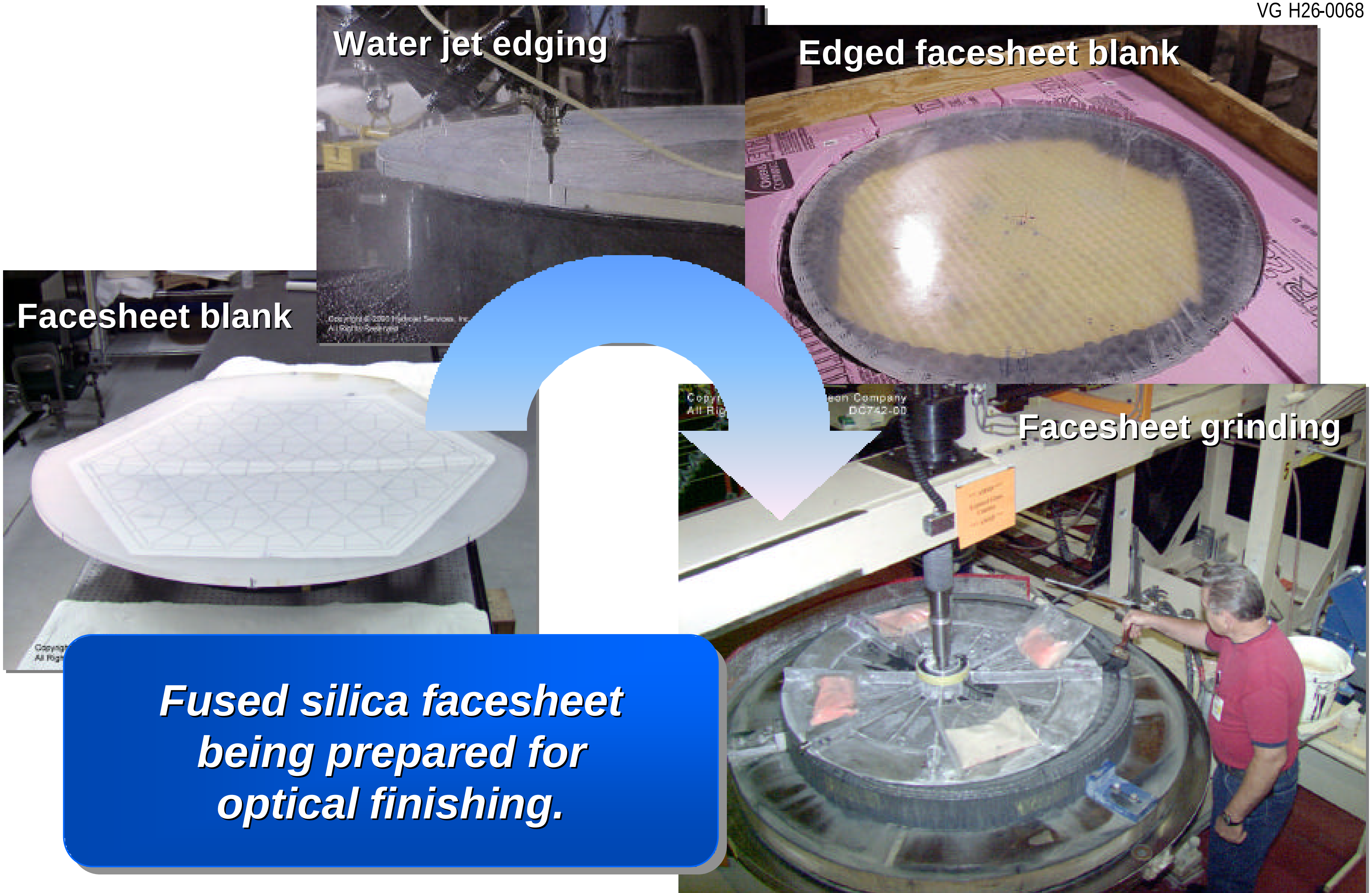
Facesheet Design

- **Material is fused silica for CTE homogeneity (but could be ULE)**
- **Isogrid provides stiffness for 1-G support**
- **Isogrid provides flexibility for figure control**



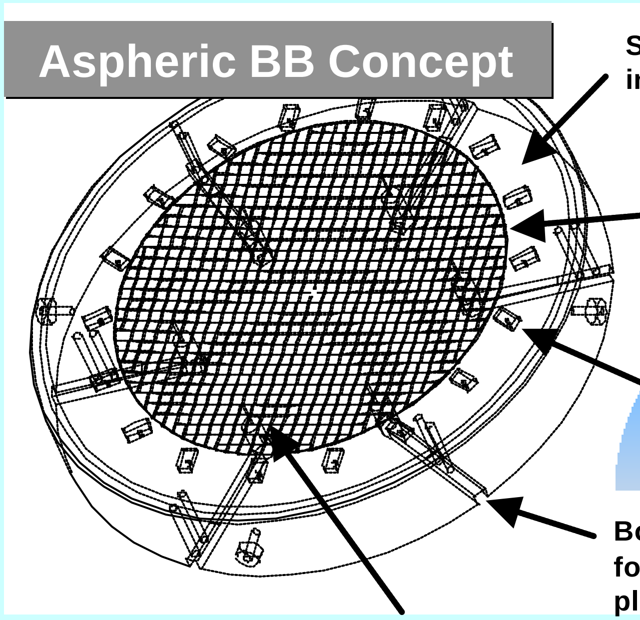


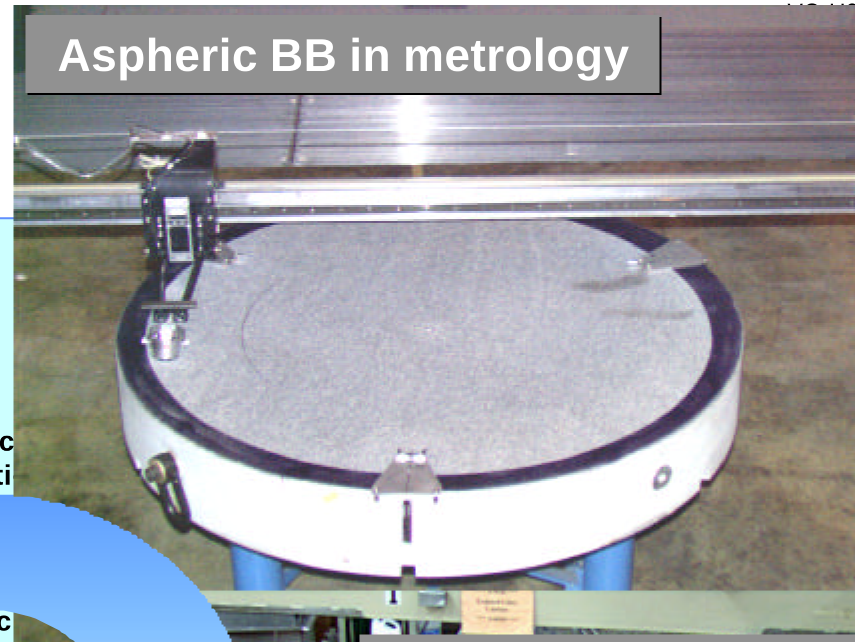
Optical Fabrication:
Preparing the Blank for Optical Finishing



Fused silica facesheet being prepared for optical finishing.

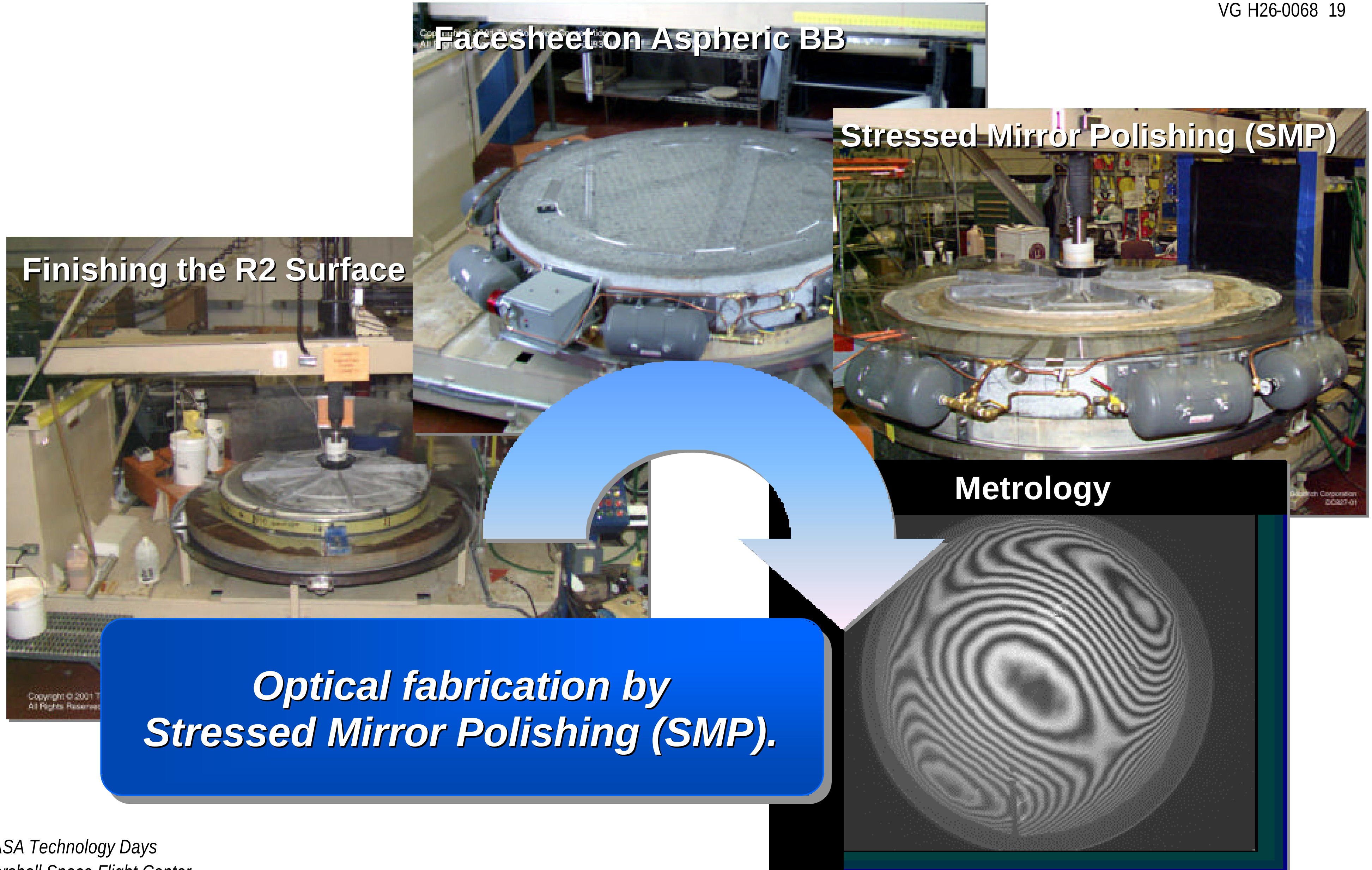
Optical Fabrication:
Preparing the Aspheric blocking Body





Fabrication of aspheric blocking body for SMP.

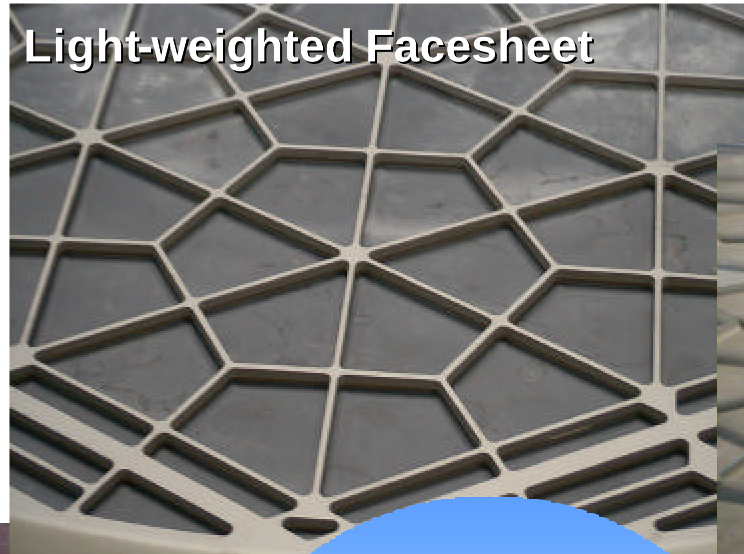
Optical Fabrication:
Optical Finishing by SMP

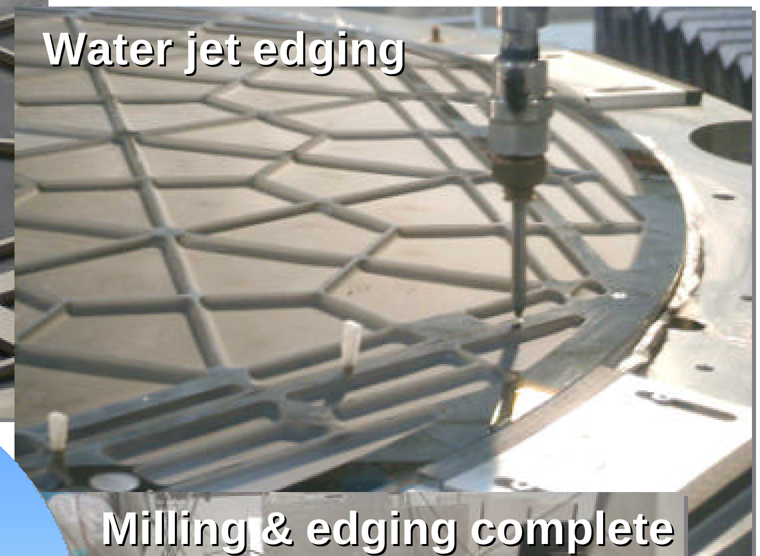


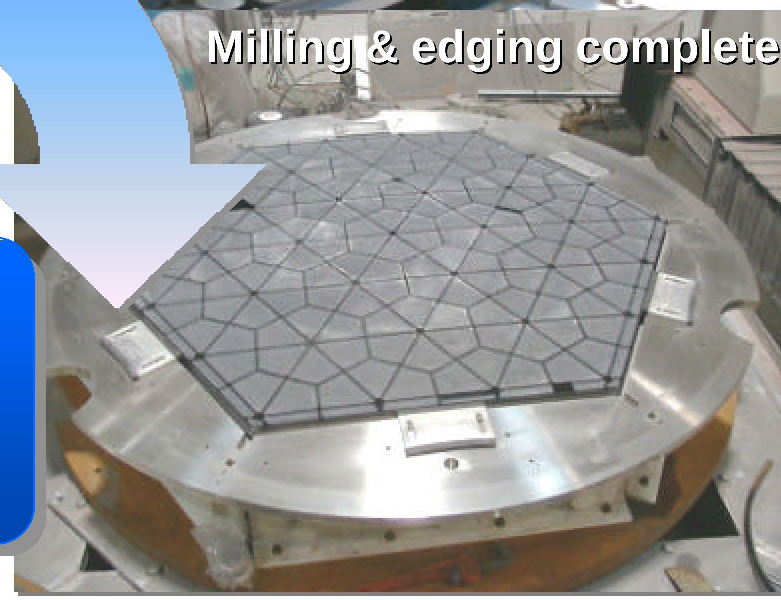
Optical Fabrication:
Tooling for Water Jet Milling

Preparing the tooling for water jet light-weighting.

Optical Fabrication:
Light-Weighting and Edging







Light-weighting the Facesheet by water jet milling.

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Optical Fabrication:
Fracture and Recovery

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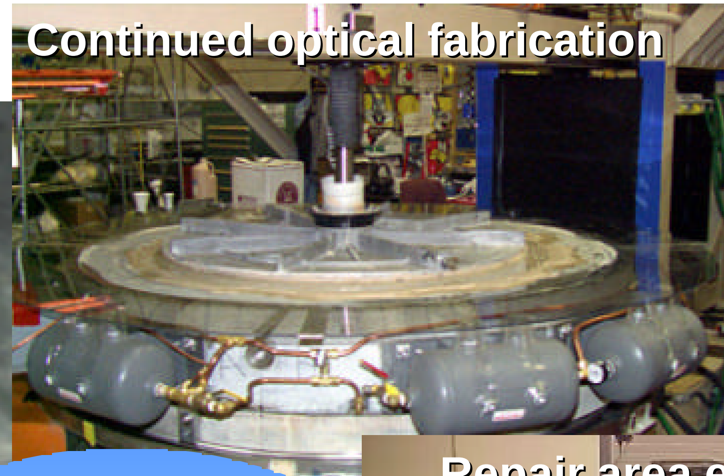
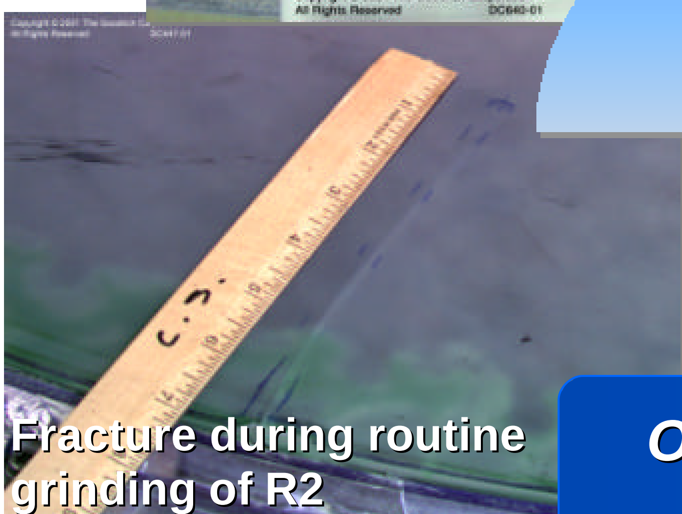




Optical fabrication completed as planned; no loss of actuators.

Facesheet Status

- **Facesheet Progress and Status:**
  - **Fracture "repair" complete**
  - **Optical fabrication by SMP complete**
  - **Light-weighting by water jet milling complete**
  - **Edging by water jet complete**
  - **Beveling and stress relief in progress**
  - **Preparations for Facesheet Subassembly underway**

Optical fabrication complete;
Stressed Mirror Polishing advantages demonstrated.

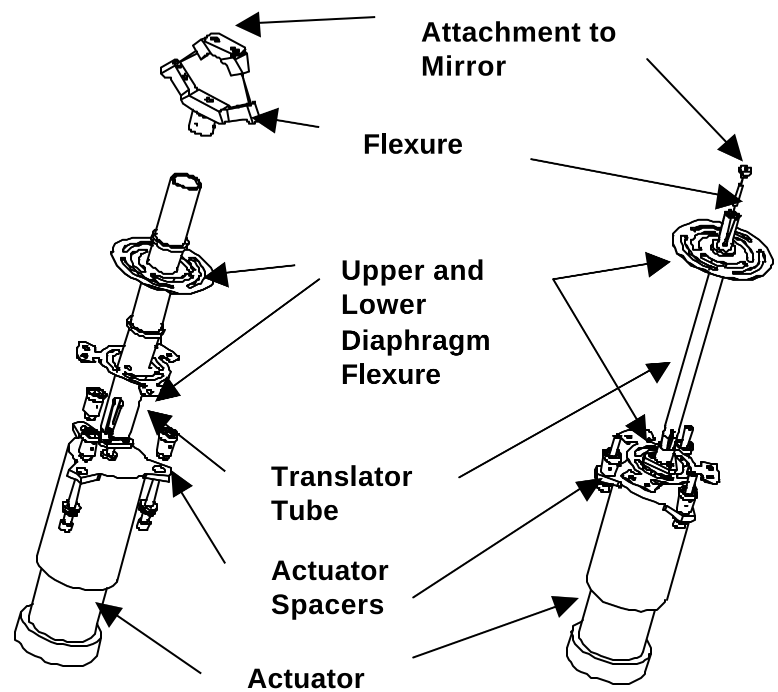
Actuators and Controller:

– Design overview

– Controller

– Test results

– Status

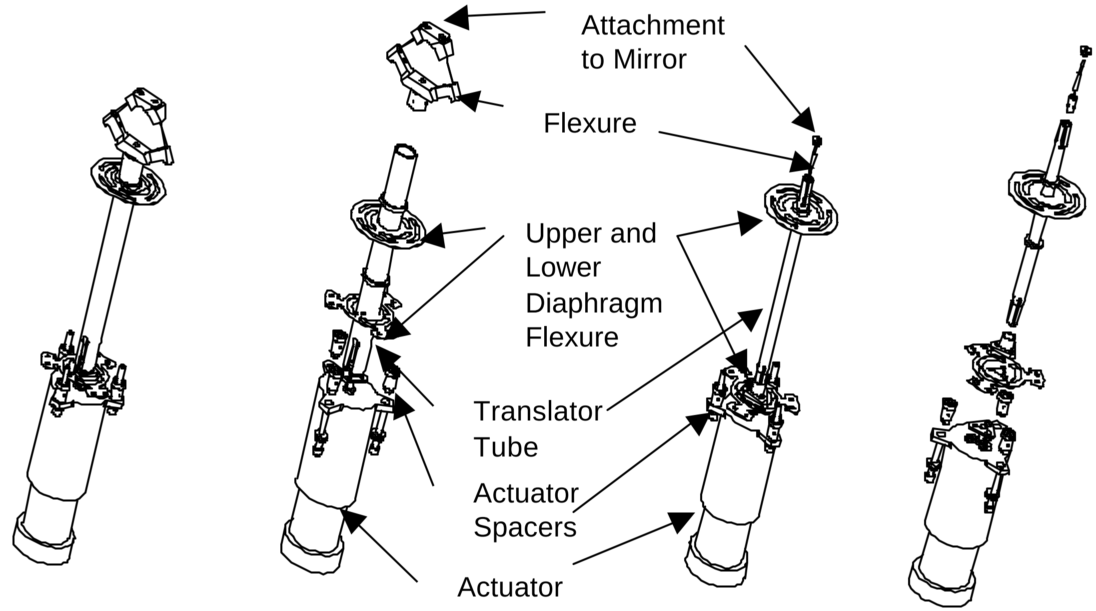


Bipod Assembly

Axial Assembly

Actuation System Design

- **Actuator assemblies (6 “Bipod”, 31 “Axial”) react all loads**
- **Similar to HALO (also cryogenic)**
- **Upper and lower diaphragm flexures stabilize translator & flexure, provide shear and moment load path for bipods**
- **Allows easy access to actuators for installation and servicing**



Bipod Assembly **Axial Assembly**

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Actuator Design Parameters Summary

Performance Parameter	Reason
Stroke	Ground test and post-deployment capture range
Resolution	Performance (quantization)
Mass	Observatory flow-down
Reliability and Lifetime	Maintain low performance risk
Room and Cryogenic Performance	Operational performance and efficient ground-test strategy
Low (zero) Power Dissipation	Thermal maintenance Operational efficiency
Axial Stiffness	PMA Dynamics
Compatibility with Cryo-Appropriate Command/Power Structure	Minimize wire count for deployment Maintain reliability and redundancy

- **Goodrich has selected stepper-motor based actuator from Moog-Shaeffer Magnetics Division (SMD):**
  - **Derived from NASA-funded cryo actuator studies**
  - **Engineered under Goodrich and Moog IRAD**

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Actuator Design:
Space Rated Materials for Cryogenic Operation

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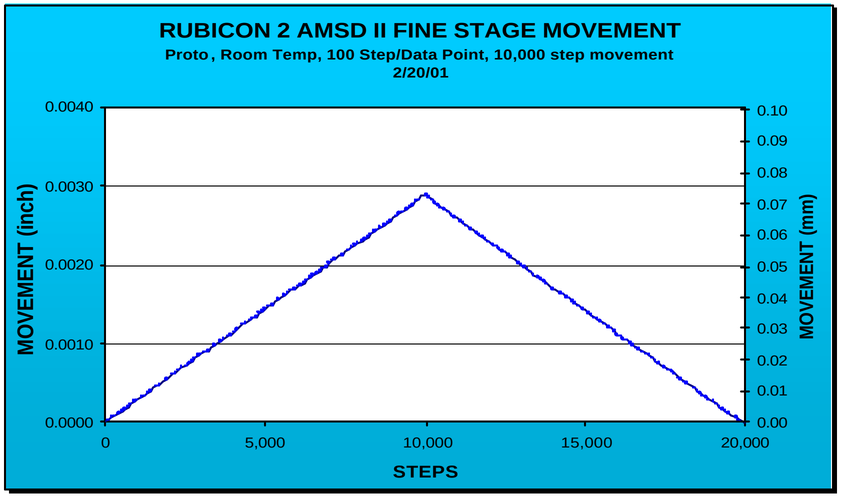
Titanium Alloy (6AL-4V)	General Construction: Housing/Transducer, Motor Housing, Thrust Rod, Spring/Nut Element, Output Flange
Stainless Steel (440C)	Bearings, Harmonic Drive Wave Generator
Stainless Steel (Nitronic40)	Output Leadscrew
Stainless Steel (15-5PH)	Harmonic Drive Circular Spline and Flex Spline
Stainless Steel (416)	Motor Rotor

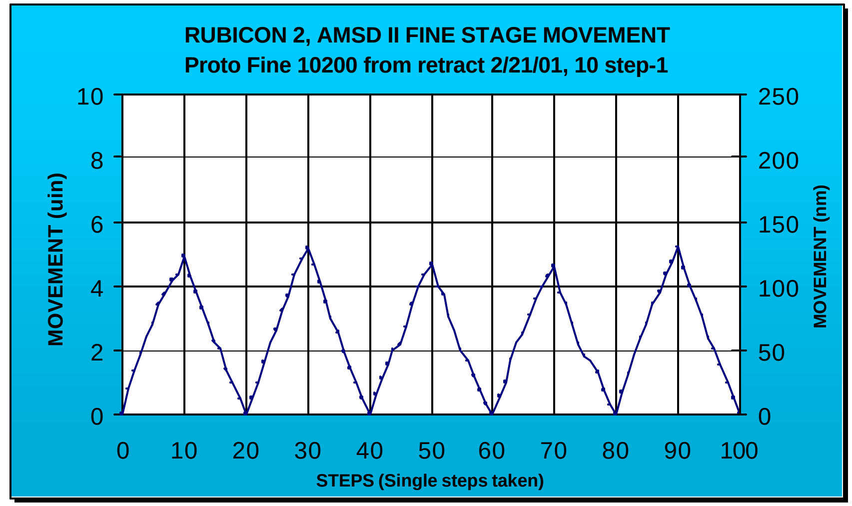
- Actuator internal bearings, harmonic drive wave generator, lead screw/nut use dry lubricant for low room temperature friction and excellent molecular bonding
- Materials are selected specifically for cryogenic application and compatibility
- Structural members are sized to perform over life with ample margin
- Fasteners are generally titanium with only a few 416 stainless steel (thermally matched)

Performance demonstrated at 30K, consistent with AMSD requirements.

Actuator Design
Verified at RT and Cryo

Room temperature tests:





Example Data:

- Average Step Size = 7.3 nanometers
- Standard Deviation = 3.5 nanometers
- Meets requirement for max. step size < 20 nanometers

RT vs. Cryo Performance:

- Same general behavior when unloaded
- Some units have exhibited anomalous behavior under load at cryo
- More extensive cryo tests underway

Actuator Electronics:
Design Requirements

- **Architecture must be traceable to deployable, space-borne applications**
- **Minimize wire-count between nodes and central controller**
  - **Hold actuator position with minimal actuator power**
  - **Minimize overall power dissipation**
- **Architecture must be scaleable to large arrays of actuators**
- **Circuit design must be traceable to operation at 30K**
  - **Operate over temperature range from 30 to 293K**
  - **Active devices MOS (bipolar processes freeze-out at T < ~70K)**
- **AMSD Electronics design does not limit bandwidth**
  (» 0.1 Hz update rate)

Actuator Electronics: Architecture

- **Control Computer (CC) and array of actuator nodes form “ring”**
  - Serial communication minimizes wire count
  - Resistive isolation between nodes prevents fault propagation
  - Easily provides required throughput
  - Ultimate bandwidth limit is motor dynamics
- **All system “intelligence” in software executing on CC**
  - Directly commands motor windings to desired states
  - Operationally flexible, upgradeable
- **“Dumb” hardware at nodes**
  - Translate winding state commands to winding drive currents
  - Minimizes hardware complexity, maximizes system flexibility
- **Topology is inherently scaleable**
  - Change CC software required
- **AMSD drive electronics are “warm” (located outside vacuum chamber)**

Actuator Electronics/Controller

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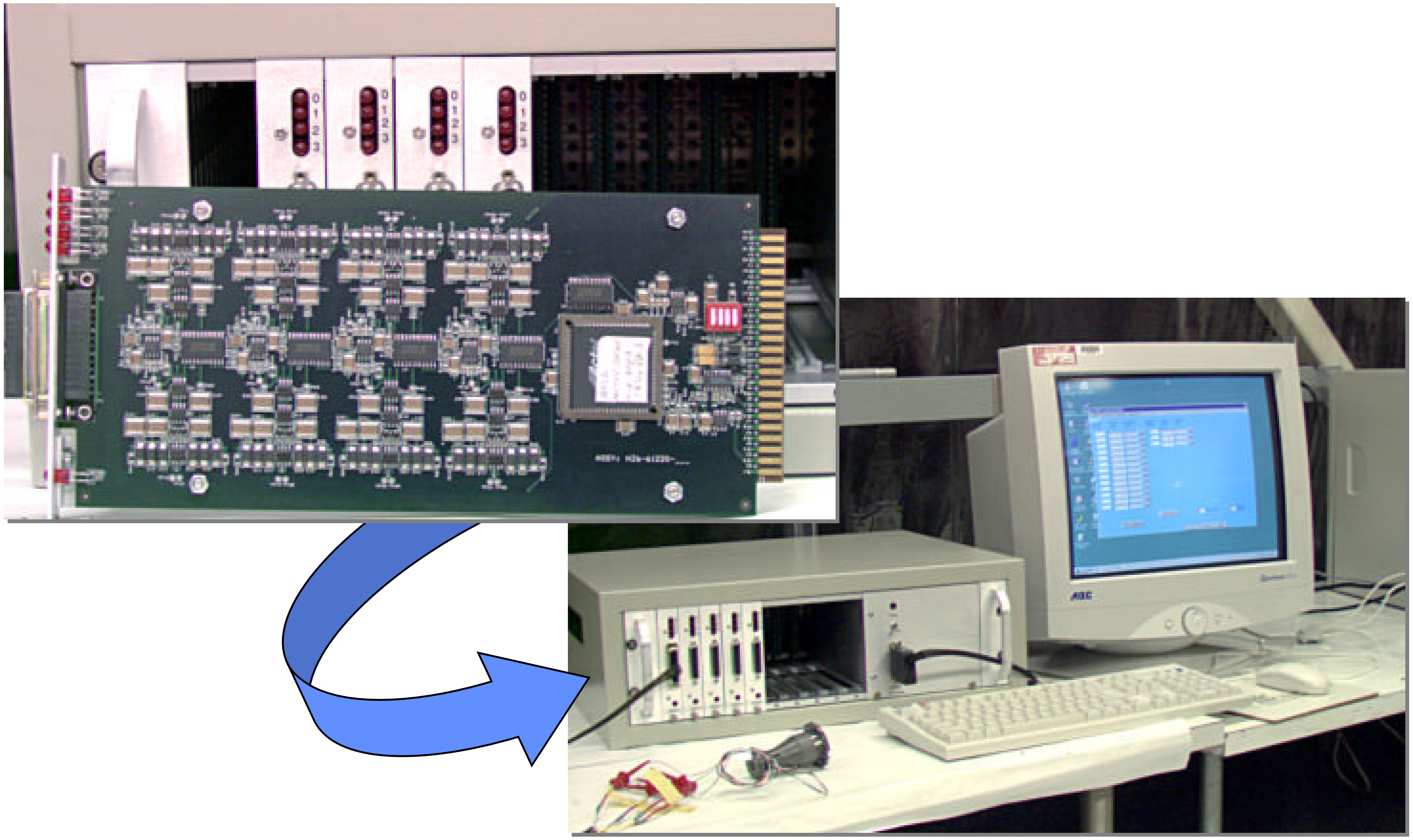
AMSD 4-channel Actuator Driver Circuit Card



Drive electronics, controller, software and cabling are complete.

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Actuators/Controller: Status

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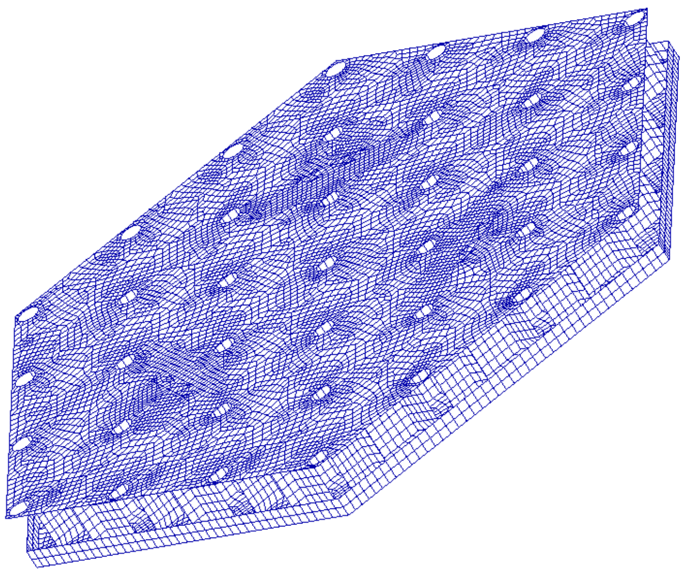
- **Actuators/Controller Progress and Status:**
  - **All 37 AMSD units have been delivered**
  - **Drive electronics and controller complete**
  - **Performance tests at RT complete**
  - **More extensive cryo testing under load underway**
  - **Integration of actuation components with Reaction Structure underway**

All actuators delivered; basic design/performance verified.

Progress Update and Status

- **Composite Reaction Structure:**
  - **Design and construction**
  - **Modeling**
  - **Delamination and repair**
  - **Cryo test results**
  - **Status**



CRS: Design and Construction

- Graphite cyanate-ester for CTE match with glass Facesheet
- Mounts actuators and flexures; reacts loads from masses and figuring
- Interfaces to external mount
- Designed and manufactured by ATK

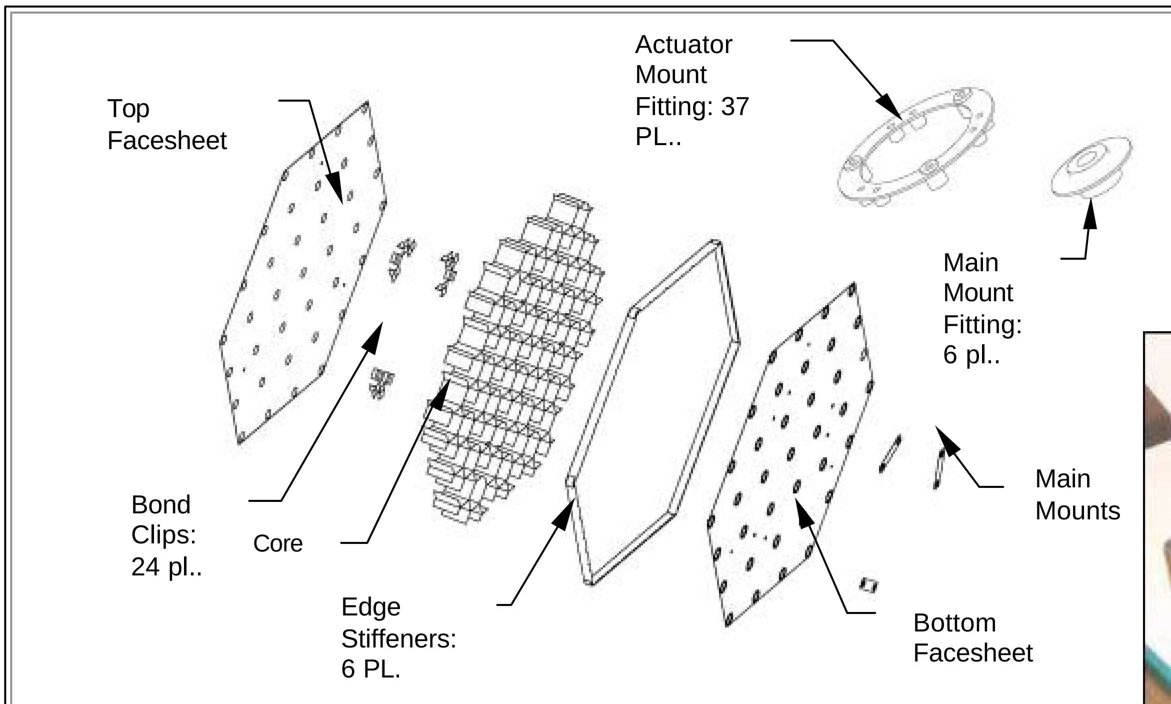
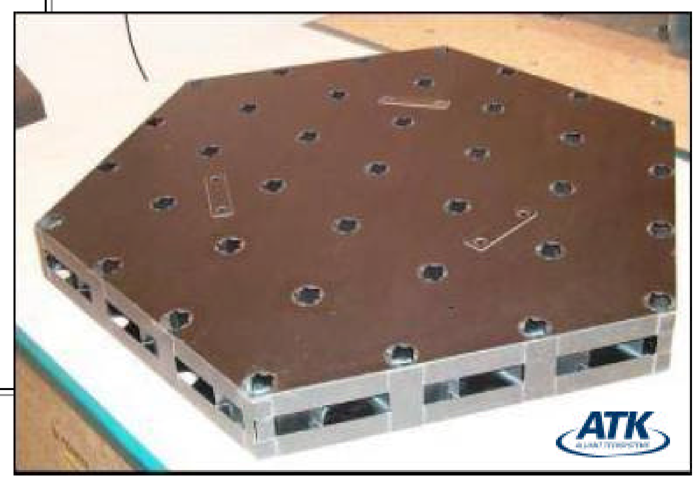
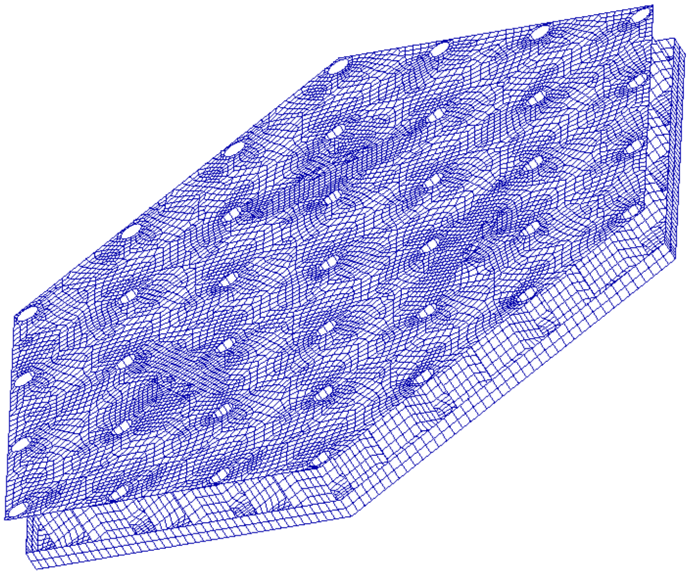
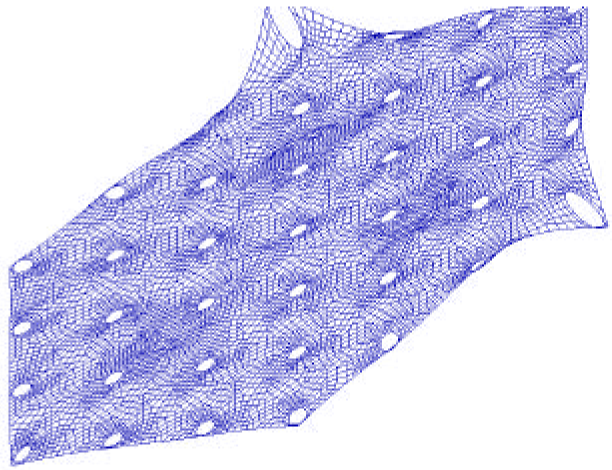


Photo of completed unit



CRS: Modeling and Analysis



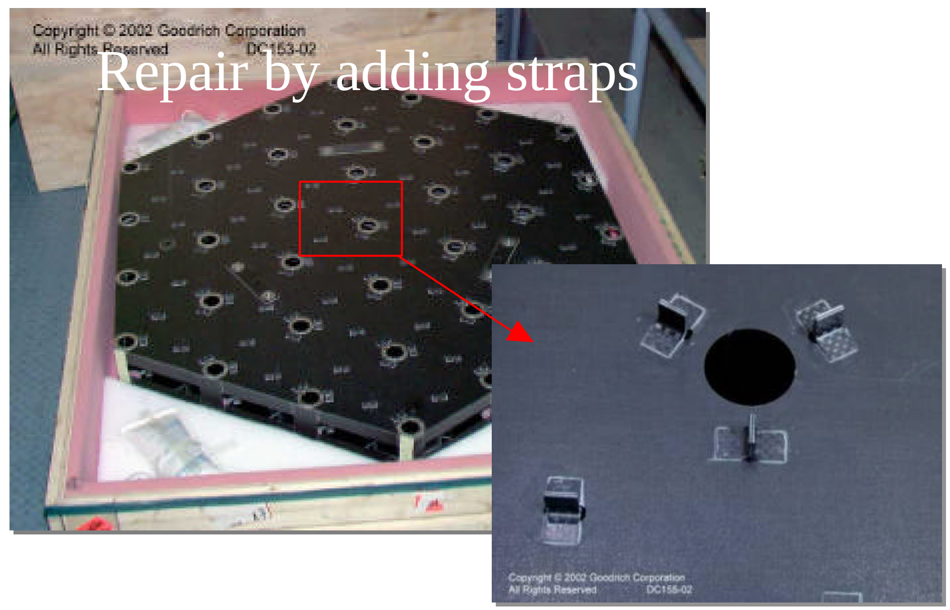


- **NASTRAN Detailed Finite Element Model**
  - **Layered shell elements**
  - **37 concentrated mass elements representing actuators and INVAR fittings**
  - **Simple support at main mount locations**

- **Predicted response of baseline structure meets requirement (1st mode reduced to due to repair)**

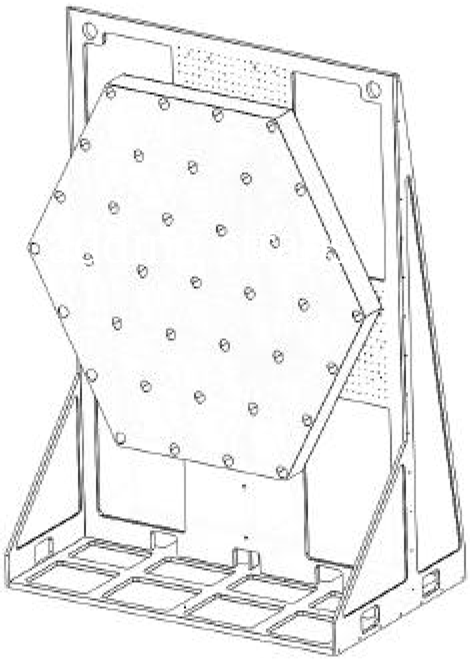
CRS: Delamination and Repair

- **Post cryo cycling inspection revealed voids in facesheets:**
  - Voids at specific orientation over core ribs
  - Attributed to alignment of facesheet plies relative to core cells
- **Repaired by composite straps between top and bottom facesheets:**
  - At every location of actual or likely delamination
  - Repair complete
  - CRS cryo cycled at the XRCF
- **Origin of failure and solutions identified**



CRS: Tests and Results

- **Tests conducted on repaired CRS:**
  - **Thermal cycle to 25 K at XRCF**
    - No metrology for distortion
    - No further delamination
  - **10-G static load test at ATK**
  - **Thermal characterization at XRCF**
    - Instrumented for distortion measurements
    - Two cycles to 25 K
    - Measured distortion within acceptable limits



CRS on cryo test stand at XRCF

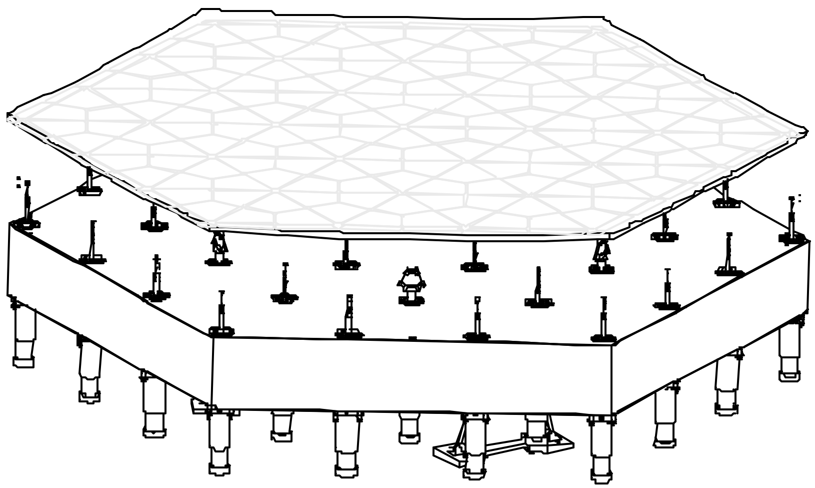
CRS: Status

- **CRS Progress and Status:**
  - **Fabrication complete**
  - **Delamination:**
    - Causes and solutions identified
    - Repair complete
  - **Cryo test of repaired unit complete**
  - **Integration with actuation system underway**

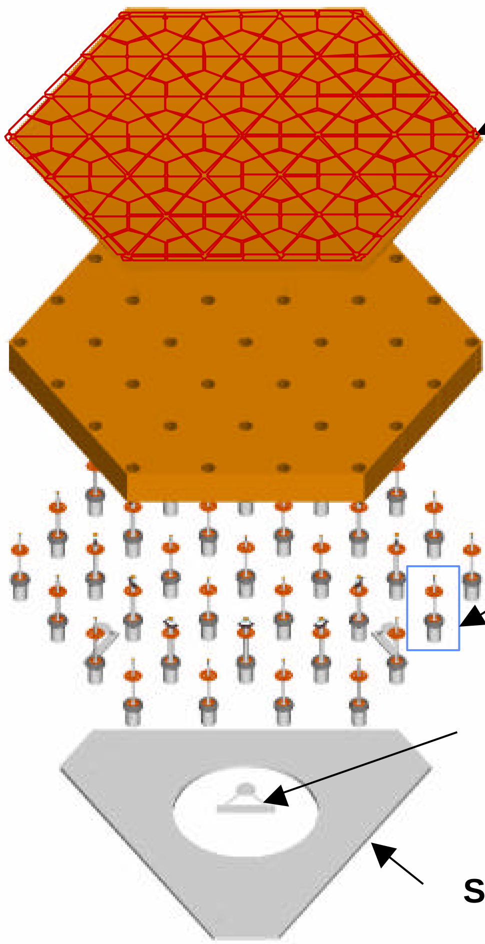
CRS complete and verified by analysis and measurement.

Progress Update and Status

- **Assembly and Integration:**
  - Assembly description
  - Integration process
  - Status and Plans



Assembly Description



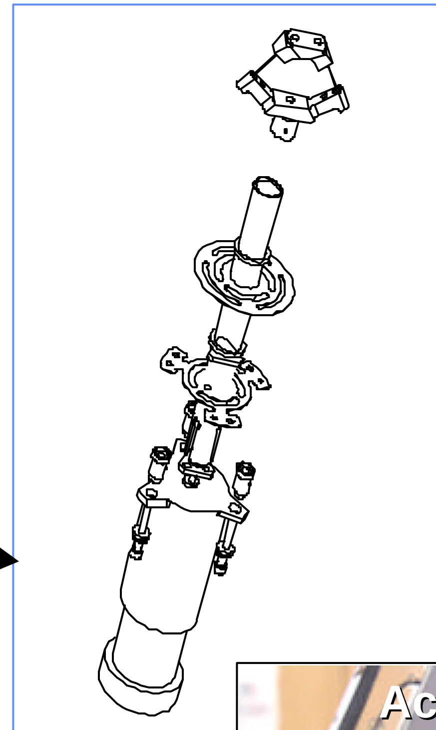
Facesheet

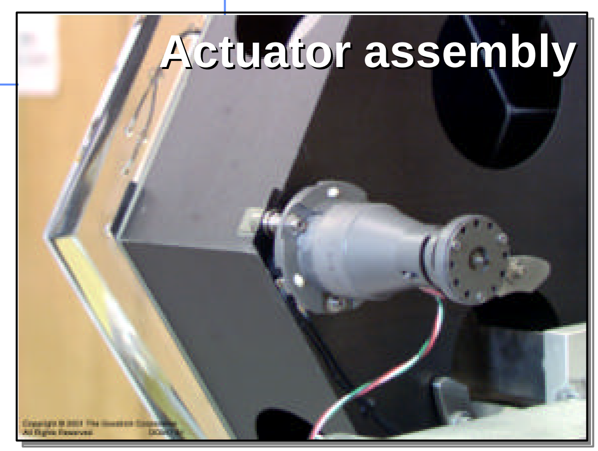
Reaction Structure

Actuators & Flexures
(37 places)

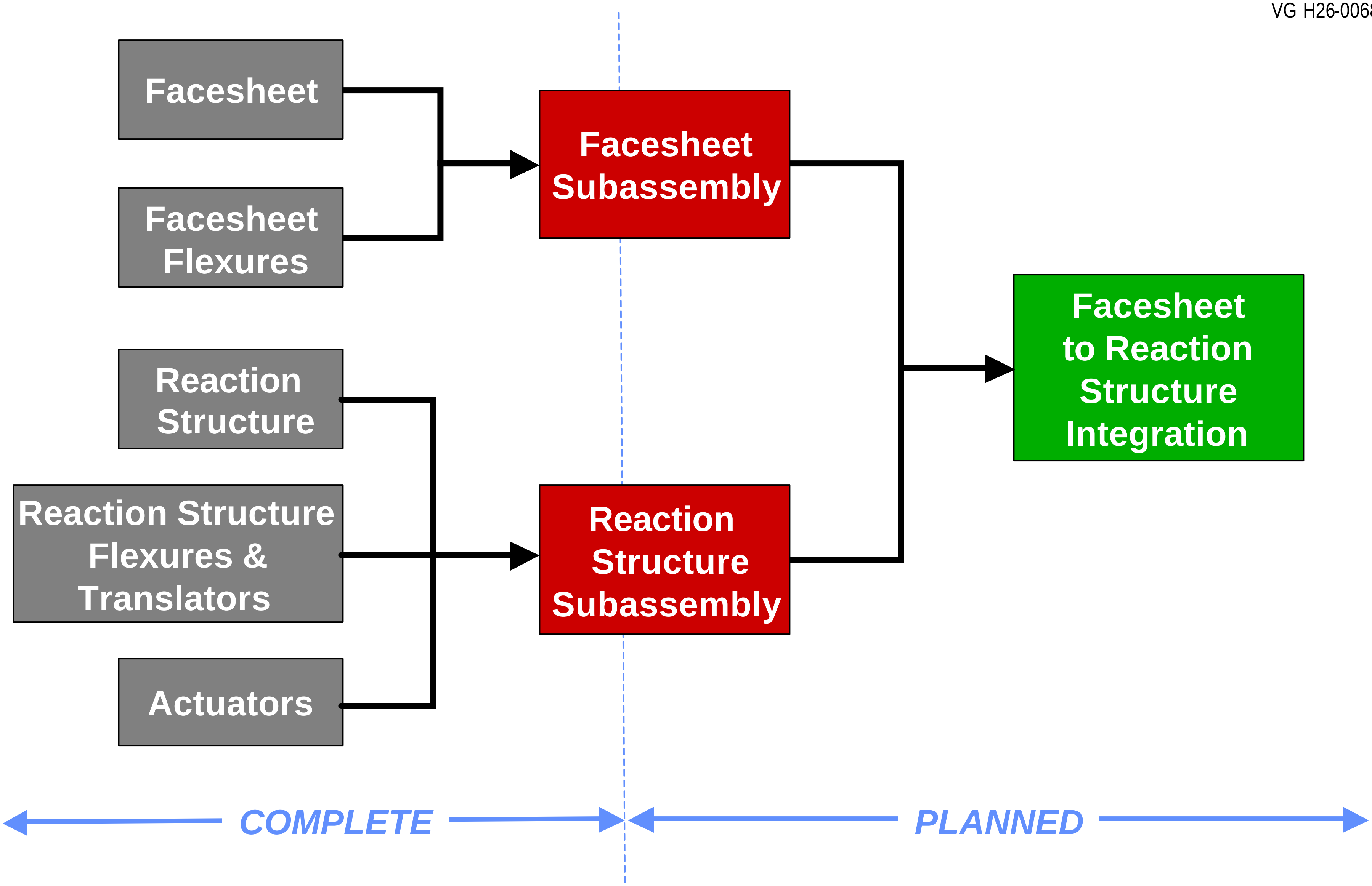
Assembly Support Flexure
(3 places)

Supporting/handling Frame





Hardware Integration Flow



Assembly and Integration: Status

- **Assembly and Integration Progress and Status:**
  - **Design and process definition complete**
  - **Tooling design and fabrication partly complete and continuing**
  - **Reaction Structure/Actuator subassembly in progress**
  - **Preparations for Facesheet Subassembly underway**

Assembly and Integration in progress per plan.

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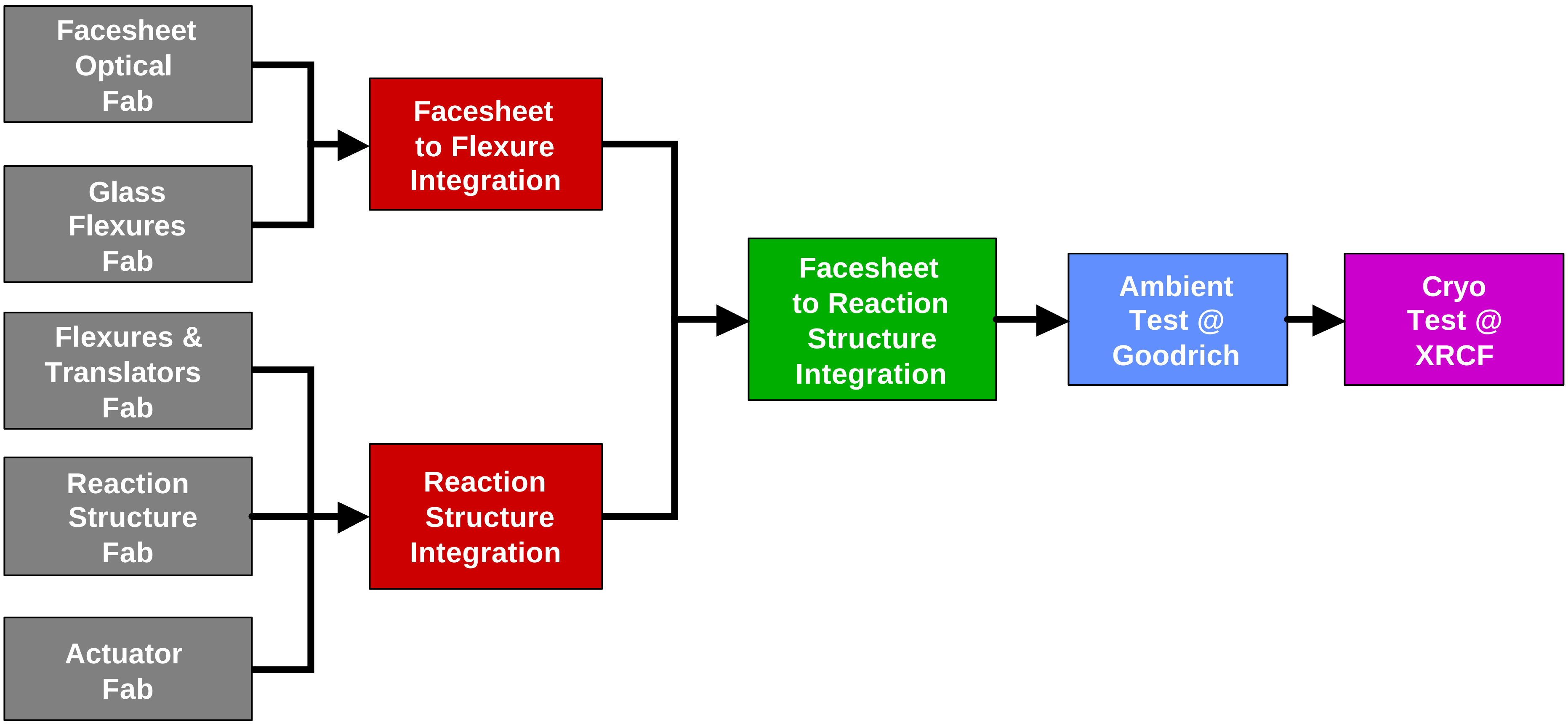
Process Flow Summary



Test & Verification
(RT at Goodrich)

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Actuator Attach Test → **Figure Actuators** → **Interferometry** → **Modal Test** → **CCP (As Required)** → **Final Ambient Optical Testing** → **Ship To MSFC for Cryo Testing**

(Final Ambient Optical Testing → CCP)

Actuator Attach Test

Verifiy actuators attachment

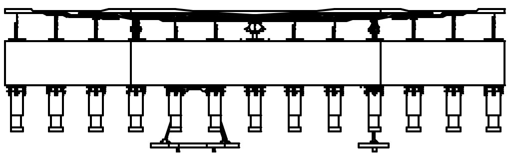
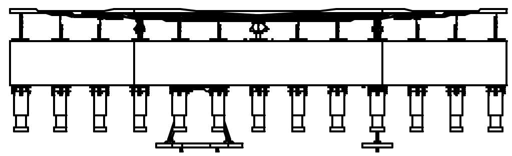


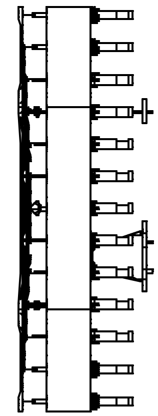
Figure Actuators

Optimize figure



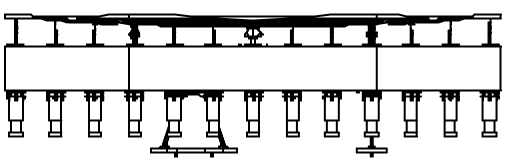
Actuator “zero” can be reset using manual coarse adjust

Interferometry

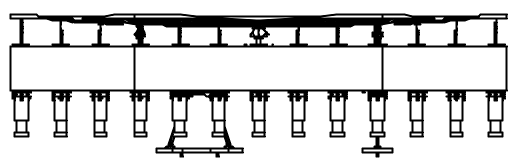


Modal Test

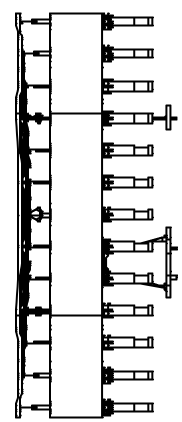
Modal survey using low-level excitation



CCP (As Required)

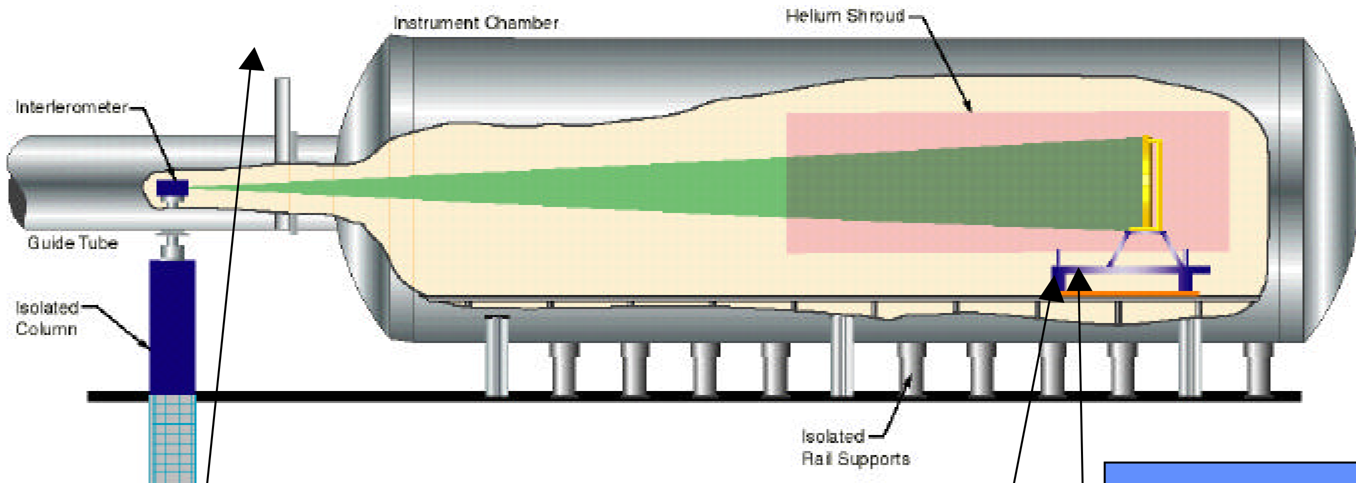


Final Ambient Optical Testing



Ship To MSFC for Cryo Testing

Cryo Test Arrangements at the XRCF



MSFC provides:
- Interferometer
- Objective Lens
- Leica ADM
- Window
- DNC

Goodrich provides:
- In-chamber cabling for actuators & temp. sensors
- Out-chamber cabling for actuators
- Mirror Assembly temp. sensors
- Actuator Control Electronics & PC

MSFC provides:
- Vacuum feedthroughs
- Cabling to control room
- Temp. sensor's readouts
- 5 DOF positioning table

- Establish ambient baseline alignment
- Measure ambient baseline figure

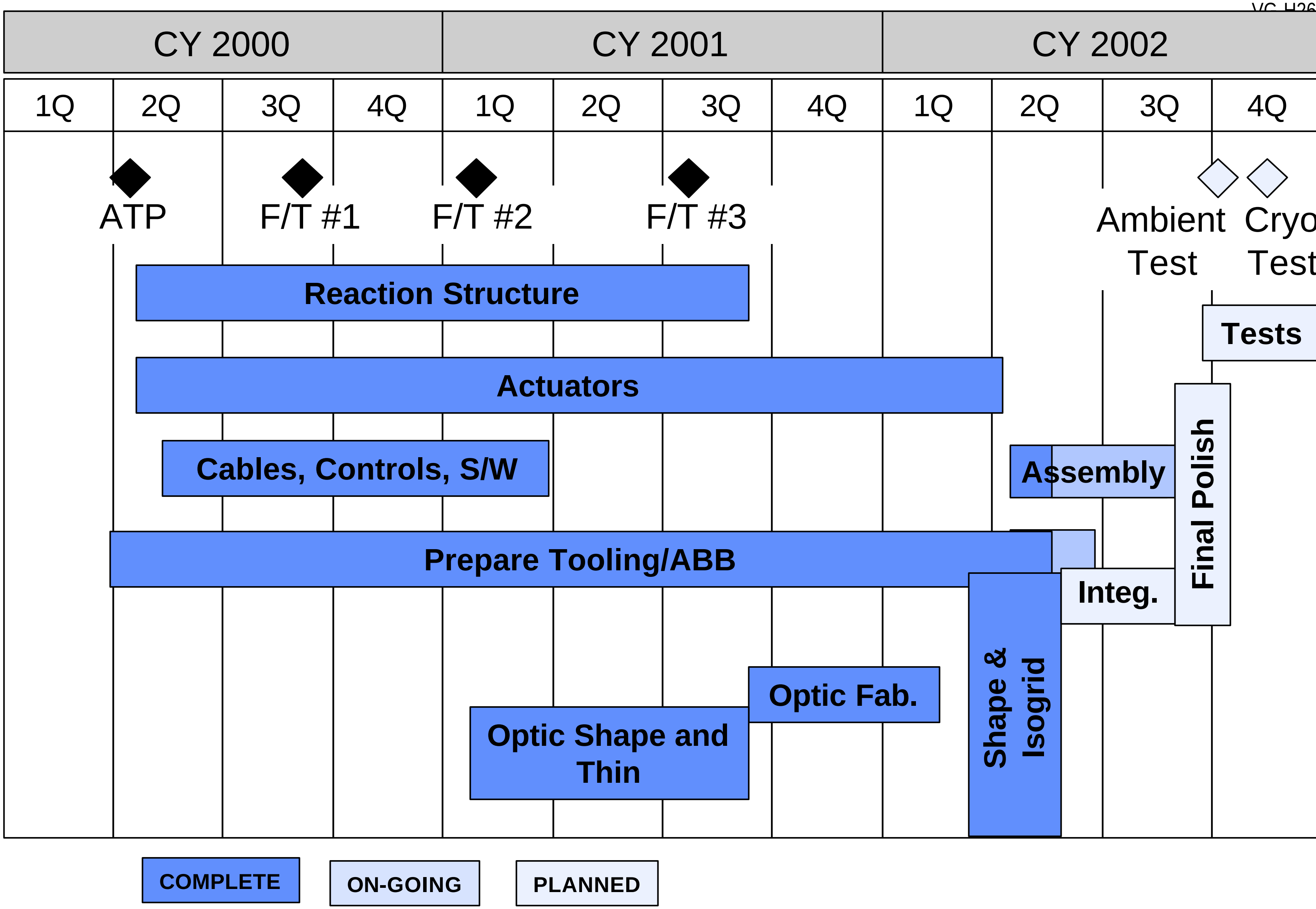
→ Partially cool chamber

→
- Measure figure
- Adjust figure actuators as required to minimize figure error
- Track actuator and despace changes over temperature range

→
- Measure figure at cryogenic operating temperature

Top-Level AMSD Program Schedule

(as of 5/22/02)



Agenda

- Program Objectives and Requirements
- Goodrich Configuration Overview
- Progress Update and Status
  - Facesheet
  - Actuators and Controller
  - Reaction Structure
  - Assembly and Integration
- Test Plan and Program Schedule
- **Summary and Conclusions**

Design Traceability Overview

- **Our AMSD design is traceable to operational systems:**
  - **Flexible facesheet** *enables efficient figuring of a readily produced substrate*
  - **'Displacement' type actuators** *stiffen facesheet against reaction structure while providing shape control*
  - **Reaction structure** *utilizes a high stiffness-to-mass material that is amenable to efficient structural forms*
  - **Material choices** *can be tailored to specific applications (facesheet and/or reaction structure)*
  - **'External' actuator** *permits adoption of improved designs*
  - **Mass and stiffness changes** *are addressed without disruption to key facesheet/actuator design and manufacturing details*

Our AMSD design is fully traceable against the SOW requirements.

Summary

- **Goodrich's AMSD architecture provides robust accommodation for a broad range of system and mission requirements:**
  - **Readily accommodates alternative petal geometries**
  - **Readily accommodates alternative materials**
  - **Provides opportunity to trade mass, stiffness, and segment size for optimal mission responsiveness**
  - **Manufacturing technique is cost/schedule effective for multiple builds**

Rapid optical fabrication and isogridding have validated the recurring benefits of the AMSD manufacturing processes.

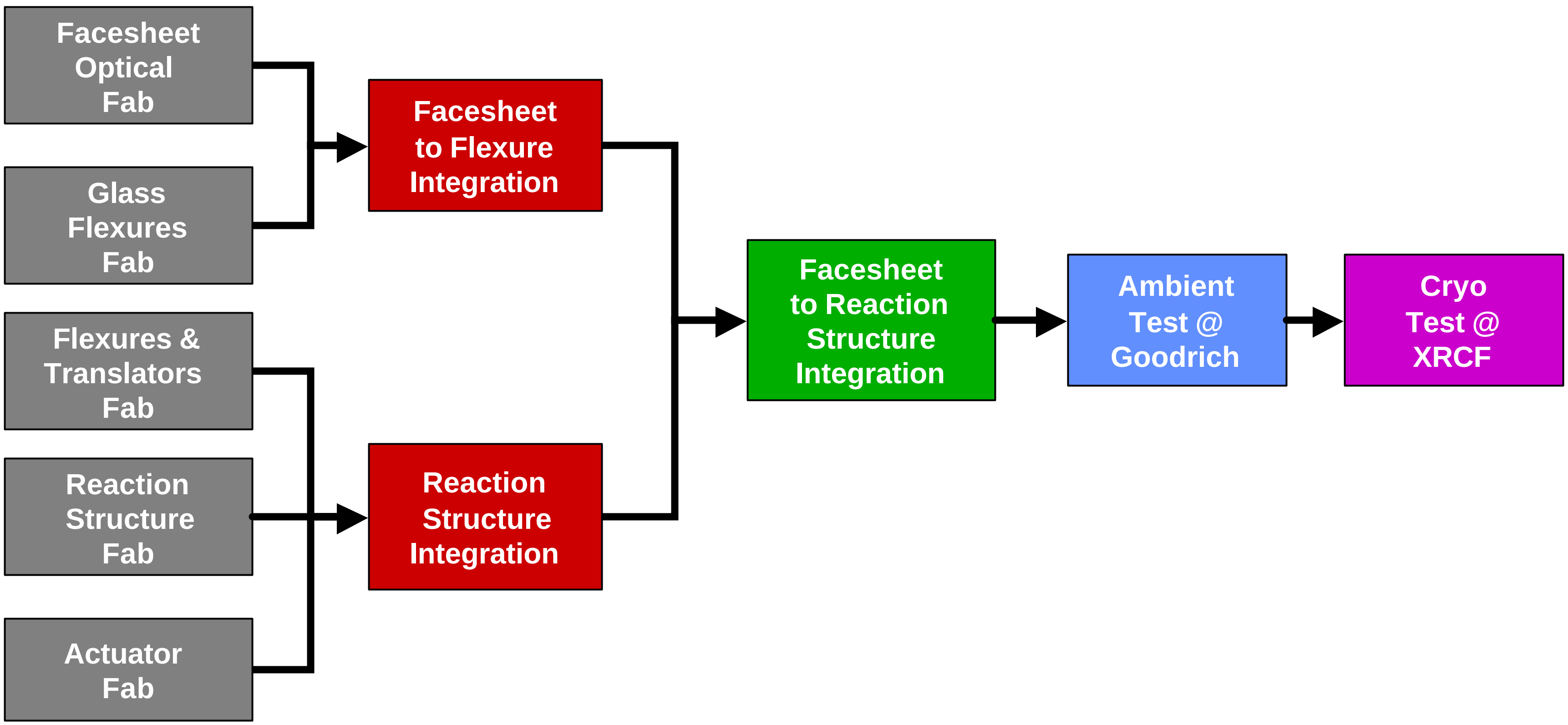
ADVANCED MIRROR SYSTEM DEMONSTRATOR (AMSD)

AMBIENT AND CRYOGENIC TEST PLANS
AT
GOODRICH ELECTRO-OPTICAL SYSTEMS

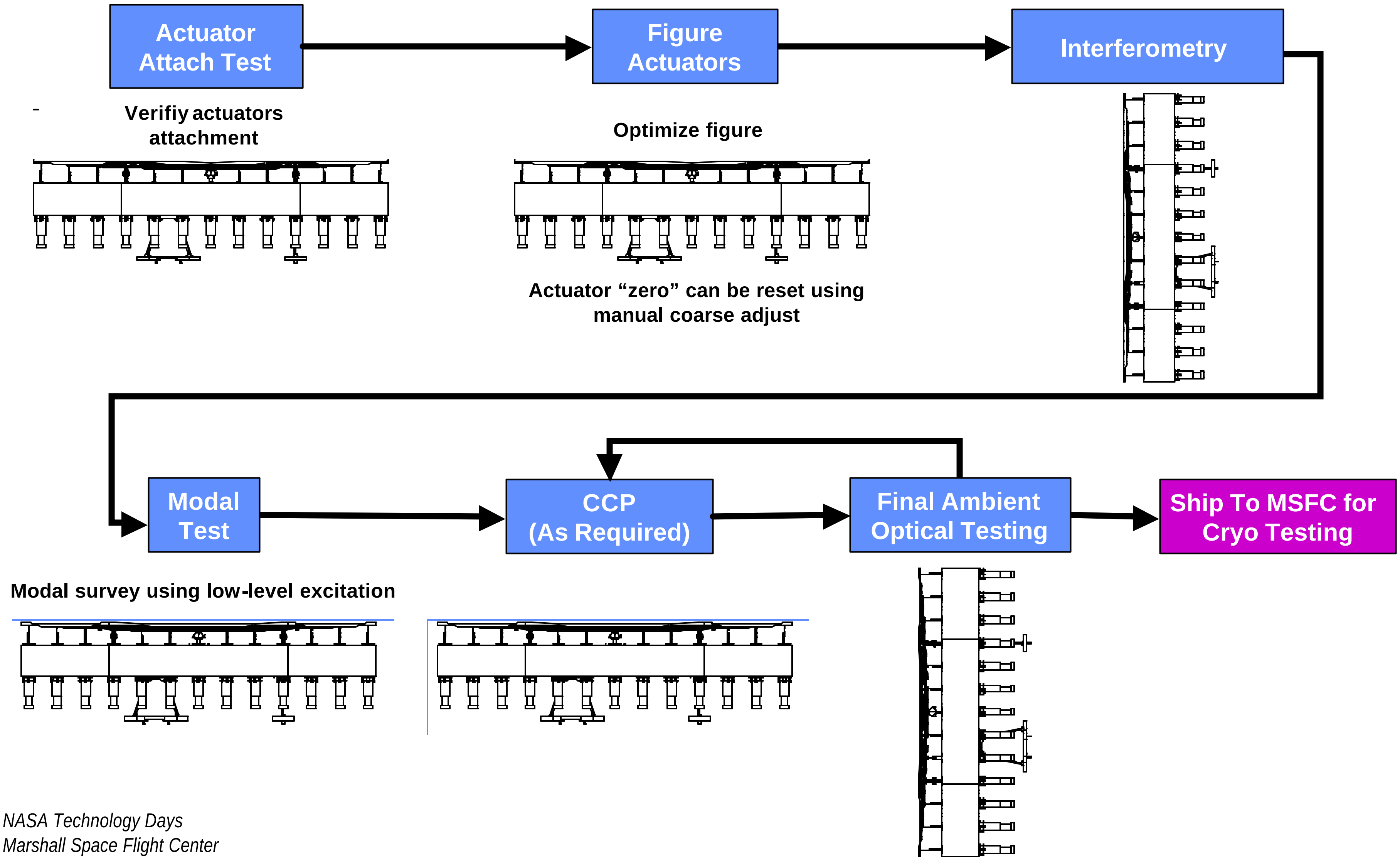
Mark Furber
Goodrich Electro-Optical Systems
100 Wooster Heights Road
Danbury, CT 06810

NASA Technology Days
Marshall Space Flight Center
May 22-23, 2002

Process Flow Summary

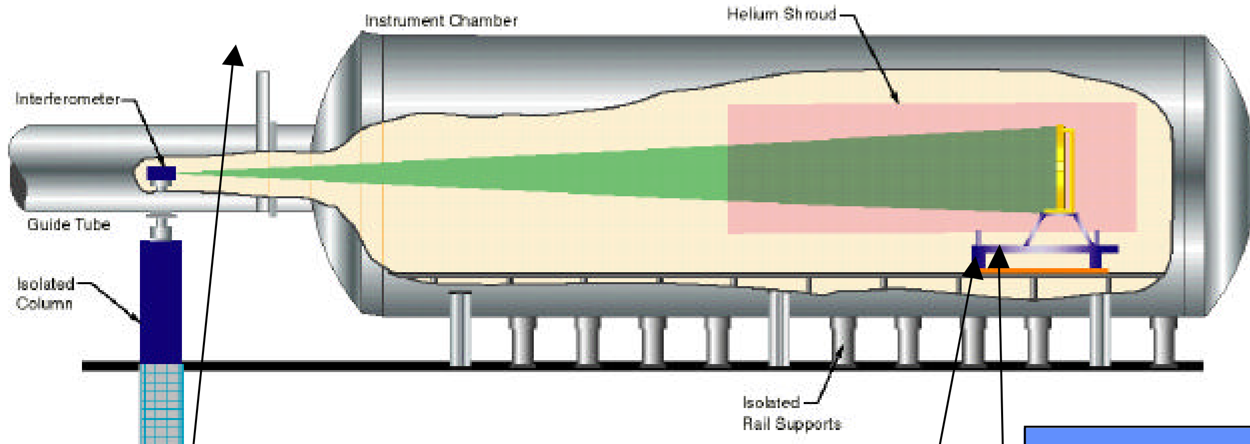


Test & Verification
(RT at Goodrich)



Cryo Test Arrangements at the XRCF

GOODRICH



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Test & Verification Plan (Summary)

- ## Ambient at Goodrich
  - **Install and align test article**
  - **Verify software and electronic functionality**
  - **Manual figure correction**
    - Visual
  - **Determine noise levels (OPD, influence functions)**
  - **Influence function measurement**
  - **Optimize figure**
    - Use measured influence functions
  - **Initial data reduction**
    - Document results
  - **Pack and ship to MSFC**

- ## Ambient and Cryo at MSFC
  - **Install and align test article**
  - **Check out interferometer and software and electrical Interfaces**
  - **Room temperature characterization as done at Goodrich**
  - **Radius of curvature monitoring throughout**
  - **Cryo Test**
    - Cool down, adjusting figure intermittently as needed
    - At cryo:
      - **Check actuator functionality**
      - **Manually optimize figure**
      - **Measure influence functions & associated noise**
      - **Optimize figure**
      - **Actuator/influence function characterization measurements**
    - Return to RT, adjusting figure intermittently as needed
  - **Remove test article**

Top-Level AMSD Program Schedule
(as of 5/22/02)

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